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I, JULIE BILLINGSLEY, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2002950271 for a patent by THE COMMONWEALTH OF AUSTRALIA as filed on 19 July 2002.

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WITNESS my hand this
Twenty-third day of July 2003

J. Billingsley

JULIE BILLINGSLEY
<u>TEAM LEADER EXAMINATION</u>
<u>SUPPORT AND SALES</u>

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PATENTS ACT 1990

PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED:

"OPTICAL STABILIZATION SYSTEM"

This invention is described in the following statement:

TECHNICAL FIELD

This invention relates to controlling the attitude of a vehicle, particularly an aircraft, using external sensors such as electromagnetic radiation sensors and motion sensors.

DEFINITIONS

A number of terms will be used throughout the description of the invention. Some of these terms are defined as follows:

Field of View - the angle of space visible to the imaging device.

Ocelli - an auxiliary visual system found in many insects, evidently used for attitude control.

Horizon Stabilization System - a system that is used to determine pitch and roll angles and provide correction signals to actuators to set pitch and roll angles to what is conventionally considered 0, wings level. Used more broadly in this document to include systems that only measure, but may not actuate.

Radiation Sensor - a photodiode, camera, millimeter wave receiver, micro-bolometer and devices of substantially similar function that sense or transduce radiated energy into signals usable for digital electronic, analog electronic, hydraulic, pneumatic, or optical processing. The output may be in the form of an array of measurements or a single measurement.

"bright sky" sensor - a sensor for which an image of the sky or measurement from the sky is brighter than the ground.

"dark sky" sensor - a sensor for which an image of the sky or measurement from the sky is darker than the ground.

"grey sky' sensor - a sensor for which an image of the sky or measurement from the sky is difficult to distinguish from ground.

It is known to control the stabilization of an aircraft or ground vehicle using sensors which detect varying intensities of light. Sensors are disposed about the aircraft or vehicle so as to be able to detect the intensity of light at different positions about the vehicle.

In the simple case of an aircraft, a light detector can be placed on either side of the aircraft such as to detect light coming from the left and right sides of the craft respectively. If the aircraft rolls such as to have its left side pointing in a downward direction and its right side pointing in a corresponding opposite, upward direction, the aircraft will sense that there is less light on its left side than there is on its right side due to the fact that the ground is not as bright as the sky. Accordingly, appropriate control signals will be applied to controlling elements of the aircraft to cause it to orient itself so as to equalise the light intensities on either side of the craft.

Gradients or steps of intensity between the sky and ground can be used to more finely stabilize an aircraft or ground vehicle. In the simple case, considering ultraviolet or blue sensors looking laterally outwards on the right and left side of a vehicle, simply balancing the left and right intensities will ensure that both sensors are looking at the horizon. In the case of blue and ultraviolet, the sky is much brighter than the ground. A full implementation of this concept is shown in figure 1, where 1 is a left looking radiation sensor and its associated field of view, 2 is forward looking, 3 is right looking, and 4 is aft looking. Each of the sensors is mounted to the aircraft 5, such that is it able to see the environment in the direction of view. In the vertical plane the sensors are arranged to look outwards with the centre of the field of view aligned with the horizon. In figure 1 the arcs 6 and 7 show the alignment and representative size of the lateral fields of view.

Fields of view of the different sensors 1-4 may be tailored to the application, with favourable characteristics gained from wide fields of view.

This system has been proposed by Kelley in [1], and foreshadowed by Stange in studies of dragonflies [2] and by Taylor in studies of locust [3] [4]. The control law proposed in each of these works was that the aircraft (or insect) would tilt away from the dark side, with the consequence that the equilibrium point has both radiation sensors registering the same light level, in an ideal environment with a flat horizon the wings would be level, considering figure 2, the aircraft is flying towards the observer, examining the signal on the left and right lateral sensors. When the posture of the aircraft is "rolled left", the right sensor sees more sky and the left sees less. In the case of a sensor that sees a bright sky and dark ground the right sensor will have a higher output than the left in this case. Clearly if the device sees a bright ground and dark sky the result will be reversed. When the aircraft is rolled right, in figure 2, 2, the imbalance between left and right sensors reverses. Only when the craft is flying with wings level, in figure 2, 3, do both sensors register the same output signal. The same rule may be applied on the pitch axis, for a device that looks forward and backward, the resulting equilibrium point being with body level, clearly the combination of lateral and longitudinal looking sensors would allow full stabilization of attitude in pitch and roll.

In its simplest form, this concept has been shown to be inadequate due to the requirement that the two sensors have wide fields of view, and can thus see the sun. The sun in many spectral bands is much brighter than the ground or the rest of the sky. This leads to large biases in roll and pitch angle. Use of a narrower field of view to reduce the effect leads to a device with less capability to recover from unusual attitudes, and also more prone to biases due to local horizon deformations (such as trees), and obviously catastrophic failure if the sun should fall within the field of view of the radiation sensor array.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a method of reducing unwanted effects of a source of electromagnetic radiation in an electromagnetic radiation sensor arrangement, the method including sensing a region affected by the source of electromagnetic radiation in a first frequency band of electromagnetic radiation to produce a first data set; sensing said region in a second frequency band of electromagnetic radiation to produce a second data set and subtracting the second data set multiplied by a predetermined factor K from the first data set.

Preferably, the first band of electromagnetic radiation is in the ultraviolet frequencies and the second band is in the green spectra frequencies. Preferably the source of electromagnetic radiation is the sun.

According to a second aspect of the present invention, there is provided a method of controlling the attitude of a vehicle having at least two opposing sides, each side supporting a sensor for sensing a region in a first frequency band of electromagnetic radiation to produce a first data set and a sensor for sensing a region in a second frequency band of electromagnetic radiation to produce a second data set and subtracting the second data set multiplied by a predetermined factor K from the first data set to provide a third data set and comparing the third data set from one side with a corresponding third data set from the other side said corresponding third data set being derived by a corresponding method performed on the other side; and adjusting the attitude of said vehicle such that said third data set and said corresponding third data set are substantially equal.

According to a third aspect of the present invention, there is provided a vehicle having at least two opposing sides, each side supporting a first electromagnetic radiation sensor for sensing electromagnetic radiation in a first frequency band to produce a first data set, and a second electromagnetic radiation sensor for sensing electromagnetic

radiation in a second frequency band to produce a second data set, said sensors being in communication with a means for subtracting said second data set multiplied by a predetermined factor K, from said first data set to produce a third data set for each side, and means for comparing the respective third data sets to produce a fourth data set.

Preferably, the vehicle will include means for controlling the attitude of the vehicle in accordance with the fourth data set.

According to a fourth aspect of the present invention, there is provided a vehicle having electromagnetic radiation sensors disposed on a left side, a right side and a front side, wherein the sensor disposed on the front side eliminates the need for having a fourth sensor on a rear side by treating the combination of the two lateral sensors as an intensity reference from the aft direction.

According to a fifth aspect of the present invention, there is provided a method of eliminating unwanted effects of a source of electromagnetic radiation, the method including the step of saturating bright parts of images in different spectra using either "grey sky" and "dark sky", "grey sky" and "bright sky" or "dark sky" and "bright sky" sensors.

According to a sixth aspect of the present invention, there is provided a method of controlling the attitude of a vehicle, the method including disposing two pairs of electromagnetic radiation sensors, one sensor from each pair detecting a first frequency band of electromagnetic radiation and the other sensor from each pair detecting a second frequency band of electromagnetic radiation, with the sensors of the first pair being tilted to sense a region substantially above the horizon while still sensing a portion of a region below the horizon while the sensors of the second pair being tilted such as to sense a region substantially below the horizon while still

sensing a part of a region above the horizon; determining a gradient between the sky and ground and computing angular displacement using the determined gradient.

According to a seventh aspect of the present invention, there is provided a method of controlling the attitude of a vehicle, the method including the use of a panoramic camera for computing horizon position and controlling the attitude of the vehicle in accordance with the computed position of the horizon.

According to an eighth aspect of the present invention, there is provided a method of controlling the attitude of a vehicle, the method including the use of millimeter wave radiation to measure the horizon, thus minimizing the effect of the sun.

According to a ninth aspect of the present invention, there is provided a method of controlling the attitude of a vehicle, the method including the use of anti-correlation detection to minimize the effect of asymmetries between sensors disposed on a first side and a second side of the vehicle.

According to a tenth aspect of the present invention, there is provided a method of controlling the attitude of a vehicle, the method including the use of motion detectors in each field of regard of a horizon measurement sensor to enable angular rate compensation in a stabilization control system used for the vehicle.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the following drawings in which:

Figure 1 shows a prior art arrangement of sensors on an aircraft;

Figure 2 shows a prior art use of the sensors to control the attitude of an aircraft;

Figure 3 shows the situation in which the sun is present in the field of view of the sensors;

Figure 4 shows the use of spectral opponency to reduce the effect of the sun in the situation of figure 3;

Figure 5 illustrates the use of image saturation techniques to reduce the effect of the sun in sensed images;

Figure 6 shows a motion detector circuit for controlling the attitude of an aircraft;

Figure 7 depicts a sensor along the lines of figure 6, using more radiation detectors;

Figure 8 depicts the use of panoramic sensors;

Figure 9 depicts the elements of a horizon stabilization system;

Figure 10 depicts further elements of a horizon stabilization system;

Figure 11 shows a combination of inertial and horizon sensor units; and

Figure 12 shows a sensor arrangement on an aircraft with the aft sensor removed.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The techniques and embodiments of the techniques that are presented depend on the key principle of spectral opponency, that is; comparing measurements taken at different electromagnetic wavelengths of the same scene, in order to classify the scene as sky, ground or horizon.

For example on a fine day the sky may be bright and the ground also may be bright, however the sky is blue, and the ground is strongly green/red. This discrimination may be made by comparing the measurement in green with that in blue, the region which is bright in green compared to blue is probably mainly ground, whereas that part which is bright in blue compared to green is probably mainly sky. This processing may be done very simply using digital or analog computation.

At different wavelengths the effects are more profound than simply blue against green. An example of a wavelength which is found in the sky, and much less on the ground is from blue (450nm) extending into the ultraviolet. The inverse of this situation is found starting in the near infrared (800nm) and extending into the millimeter wave, where the ground is warm or intense, and the sky is cold or dark.

Cloud cover may reduce or eliminate the contrast in the infrared. In the green and red part of the spectrum (500nm-700nm) the sky and ground are of approximately equal intensity, unless clouds are present, in which case the sky may be brighter than the ground, under clear conditions over normal terrain, green/red sensors are nearly ideal "grey sky sensors

The sun, if visible through cloud, fog, or dust, is always bright in these wavelengths, and typically brighter than any point on the ground. The difference in brightness is a wavelength dependent factor of 10 in millimetre wave bands, 100 in thermal bands, and 1000 in visible bands. Given the approximately 2° angular subtense of the sun, false attitude readings using a simple single band horizon sensor could potentially be very large. Typical sun induced errors in a single band horizon sensor would be 60° in ultraviolet, 20° in thermal bands, and 6.5° in millimeter wave bands. cloud cover is another potential source of error, as cloud may be brighter, warmer or more emissive than the ground depending on wavelength.

Logarithmic processing of intensity signals allows a much larger range of radiation levels to be measured. The use of logarithmic processing also allows computation of ratios and products straightforward even in analog hardware.

Figure 3 outlines the simple horizon stabilization concept discussed above, using ultraviolet light. The aircraft is placed into a rolled attitude when the sun is near the horizon as the controller attempts to hold both radiation sensors (1 and 2) to have equal intensity. Thus the roll command is driven directly by the two opposed radiation sensors. Since the sun increases the net light on the left side, the aircraft banks towards the left as the control system attempts to keeps the light on both radiation sensors equal. The left radiation sensor then sees more ground and less sky, and the right sees more sky and less ground, eventually an equilibrium is reached where the sensors

have equal output. The equilibrium angle is not horizontal due to the bias applied by the sun.

The solution to this problem is to consider two spectral bands, with different sky/ground contrast. An example would be ultraviolet and green. Ultraviolet is a "bright sky" sensor, green is a "grey sky" sensor. In both bands, the sun and clouds are the brightest objects in the environment. The effect of the sun is reduced by removing a proportion of the green signal from the ultraviolet signal before comparing opposite sides for stabilization purposes.

Referring now to Figure 4, the system is again positioned such that the sun is contained within the field of view of the left pair of radiation sensors, where one sensor on each side is sensitive to green light, and one on each side is sensitive to ultraviolet light. Subimages (3) and (4) show the input to the UV sensor, note the image of the sun. Subimages (2) and (5) show the input to the green sensor. Sub images (1) and (6) show the equivalent input that would produce an output from each sensor pair if a fraction *(K)* of the green signal is subtracted from the UV signal. In other words the subtraction produces the signal that would be expected if there were no image of the sun in the field of view of the sensors. Depending on the scale factor *K* and the environmental conditions, the effect of the sun can be largely mitigated or eliminated altogether.

In the case of non-imaging sensors, ie. sensors with only a single photosensitive element, or imaging sensors that are defocused to the extent that no image formation occurs, the computation follows exactly as outlined above. Some advantage can be gained if the radiation sensor logarithmically compresses the incoming signal. The advantage of this approach is that each subtraction is equivalent to a division, and thus a ratio. Thus at the first Σ in the block diagram, a ratio between ultraviolet and green light is taken, and at the second Σ a ratio of left to right ultraviolet against green

contrast is taken. The division process, easily performed using logarithmic processing, eliminates many environmental light level dependent performance changes. An example of such a performance change is that without logarithmic processing, on a day with half the green light, and half the ultraviolet light, the correction signal would be half as much, which is clearly undesirable in a dynamic control system.

In the case of imaging sensors the information can be pooled, and the data treated as a non-imaging sensor, however full advantage is not then taken of the concept outlined in the previous section. Even for a linear imaging device, such as a normal charge coupled device (CCD) or CMOS camera, the subtraction process can be used to advantage. In this case the sun and other bright objects on the ground or sky, such as clouds, metal and ice will appear bright in multiple spectra because they reflect the sun. In most cases, the sun and reflections of the sun will saturate the imaging devices, driving them beyond the linear range of pixels. In this case removal of sun artifacts can be achieved at an individual pixel level by subtracting images in different bands. In figure 5 image (1) is the green channel image, image (2) is the blue or UV channel image and (3) is the result of subtracting a fraction of (2) from (1). The green image will contain saturated contrast where the sun falls on the imaging plane. The blue image will contain sky/ground contrast, as well as the saturated image of the sun at the same angular position as in the green channel image. Since the saturation values for both spectra will be the same (limited by the electronics of the camera), a subtraction can eliminate the sun image, leaving only sky/ground contrast.
If the values of individual pixels of the array are logarithmically compressed, then the sum of the compressed values divided by the number of elements forms the logarithm of the geometrical mean of the values. The geometrical mean is less sensitive to extreme values than the arithmetic mean, and provides an alternative to a saturating nonlinearity.

The image can then be pooled to form a single intensity output. The processing of the output signals from each side of the craft then follows that outlined in figure

3.

Mitigating negative effects of horizon irregularities

Clearly the horizon can not always be counted on to be perfectly flat and devoid of features, particularly during low altitude flight. A technique for reducing the effect of horizon features is presented.

Signals from the sensors on each side of the craft should be closely anti-correlated, when one becomes brighter from receiving more sky, the opposite will become darker from receiving more ground. If the signals are not anti-correlated, then a fault condition exists, most likely due to an asymmetrical horizon. By detecting these conditions it is possible to suppress the response of the control system. Many circuits could achieve this function, we will present one that has been tested in simulation.

The Hassenstien/Reichardt correlation detector is a means for measuring a relative degree of correlation between two signals, and the associated time delay before correlation. In figure 6 such a detector is shown, with the suppression circuit. When the signals from the opposed radiation signals are closely anti-correlated the detector responds strongly, allowing the control actuation to proceed. When a signal is not closely anti-correlated the control actuator is suppressed. The actuator suppression system can allow reduced control inputs to continue to take place in order to prevent other fault conditions arising from unusual horizon configurations, or gross illumination asymmetries. Any type of motion detector could be implemented in place of the Reichardt detector, and the implementation could be digital or analog.

Scaling of platform corrections: Advanced ocelli

A difficulty with the concepts outlined above is that the correction that must be made to the platform attitude is not known in absolute terms. An imbalance between the opposed sensors indicates the direction in which the correction should be made (left,

right, up or down), but not the amount (eg. 3° roll) since light intensities vary with time, altitude, position, and weather.

The situation may be substantially mitigated by using an additional pair of sensors in each spectral band on each side of the craft. Each pair of sensors is arranged such that one is tilted substantially above the horizon while still containing part of the ground in its field of regard, and the other is tilted below the horizon while still viewing part of the sky. Thus each unit in the pair contains different but overlapping parts of the environment within their fields of regard. Thus a typical implementation would have four radiation detectors on each side of each axis to be stabilized. As will be explained below, this number could, under some circumstances, be reduced to three, with only an additional sensor in the wavelength likely to have a large gradient included.

By sampling both above and below the horizon, the gradient between sky and ground is determined. Using this information it is possible to compute angular motion, as the ratio of spatial gradient to temporal gradient in intensity levels. This is a well known method for computing motion from two or more sampling stations. Other techniques could be applied, including the Hassenstein/Reichardt detector of biological systems, however the gradient technique will return absolute angular displacement. Figure 7 shows an example implementation that includes the actuator suppression system described above, and two different control systems, one controlling angular position quickly and with high gain, and the other making smaller corrections over a longer time span. This high and low rate control is common in aircraft control systems, although typically implemented with gyroscopes. The variables A1 and A2 represent the gradient between sky and ground computed from the differences between the upper and lower electromagnetic detectors. Using variables A1 and A2, divided by the angular difference between the directions of views of the two sensors, gives a scale factor in volts per degree.

This technique would enable the optical stabilization system to perform much of the role of a rate gyroscope about the axis in question. By providing angular velocity information to the flight control system, it becomes less critical that the horizon position control is provided with absolute angular position, since large corrections are made based on accurate angular velocities, while small corrections can be made using light balance.

Another important benefit to such a system is accurate control of bank angle with no gimbaling, as the relationship between voltage imbalance and angle can be determined (variable Al and A2 in Figure 7).

Finally such a system allows detection, followed by control of inverted flight.

The above technique requires understanding that useable contrast exists with either dark sky or bright sky sensors, that green and red "grey sky" sensors will not work, In practice the gradient would be determined in the past, stored and then used while turning.

The opponent processing is required or the approach is useless since clouds and the sun would cause the gradient to vary dramatically.

Image plane analysis for attitude determination

Using a panoramic or global imaging system it is possible to undertake more complex processing to extract the true horizon position. Using the same processing concept as outlined above, of enhancing sky/ground contrast by subtracting two spectral or color channels, it is possible to determine with precision the local horizon line. Although the systems outlined above provide a mean horizon line, unbiased by the sun, they do not provide any means of removing biases in the shape of the horizon. Such biases occur in urban and natural canyons, in mountainous regions, and under trees.

The image is captured from the panoramic device. The horizon is enhanced by the process of spectral opponency outlined above. The image is then possibly converted from cartesian coordinates to polar coordinates to enhance the speed of later processing. A threshold and any required heuristics is then applied to the image to determine the location of the horizon line. By this means the ground is distinguished from sky.

The position of the horizon line is then processed to determine the best estimate of attitude. Considering figure 8, an accurate horizon is to be found when the ground subtends one hemisphere (2), and the sky subtends the other (1). Clearly this amount of information is not always available, as the terrain may be rugged. A feature of the earth is that the sky is very rarely seen *below* the horizontal plane. This is due to the size and erosion patterns on the earth, which essentially rectify the horizon, allowing sky/ground transitions above but not below the horizontal plane. From this observation it is possible to deduce which regions of the apparent horizon line are most reliable for attitude determination. Although the entire sky region of the image may not subtend 180° at every point about the perimeter, due to features on the horizon in region (4), those sections which subtend close to 180°, for example line (5), are least prone to biases. Using any two of the longest arcs, it is possible to compute the true horizon position line (3). Obviously many heuristics and a larger number of samples would lead to an even better solution, while still utilizing the basic technique. The end result of the processing will be the location of the horizon in the wide angle image, and consequently the angular position of the vertical direction with respect to the current attitude of the craft. This is the functionality required for a vertical reference system.

Aircraft control using horizon sensors

External navigation infrastructure, such as the Global Positioning System, and non directional radio beacons provide heading and position information. The assumption of these systems is that the aircraft is either upright, or can sense its true attitude with

respect to the vertical. Clearly a craft oriented at 90° to 180° from the vertical is in a dangerous situation, and any steering commands will not cause heading corrections in the right direction unless the craft is aware of its attitude. Attitude computation can be implemented using expensive and complex inertial sensors. Alternatively the simple horizon reference and stabilization systems presented here could be used. Some considerations of the nature of the sensors is required in order to produce a functional navigation system.

The simplest form of horizon sensor presented previously produces a signal that is relatively definitive in a situation where the horizon bisects the fields of view of both sensors. In order to turn, a fixed wing aircraft must either "skid" or bank. The latter method of turning is preferable, as not all aircraft are equipped with rudders, and most unmanned aircraft do not require rudders for any phase of flight. The difficulty that arises is that although the device definitively indicates the "level" condition, it does not accurately measure the angular deviation from level since contrast between sky and ground is unknown. Bank angle control would be a requirement for a GPS autopilot.

This limitation can be overcome in one or all of three ways:

The system could adaptively discover the voltage bias to hold on the horizon sensor in order to effect the desired rate of heading change.

The relationship between bank angle and sensor voltages could be determined by banking the aircraft rapidly, and then back to level while under the control of the gyros. The relationship between integrated gyro signal and ocelli voltages could then be compared to determine the sky/ground gradient as measured by the ocelli.

References

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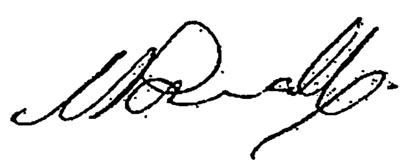
[2] G. Stange and J. Howard. An ocellar dorsal light response in a dragonfly. *Journal of Experimental Biology*, 83:351—355, 1979.

[3] C. P. Taylor. Contribution of compound eyes and ocelli to steering of locusts in flight. i. behavioural analysis. *Journal of Experimental Biology*, 93:1-18, 1981.

[4] C. P. Taylor. Contribution of compound eyes and ocelli to steering of locusts in flight. ii. timing changes in flight motor units. *Journal of Experimental Biology*, 93:19—31, 1981.

Dated this 19th day of July, 2002.

THE COMMONWEALTH OF AUSTRALIA
By its Patent Attorneys
MADDERNS



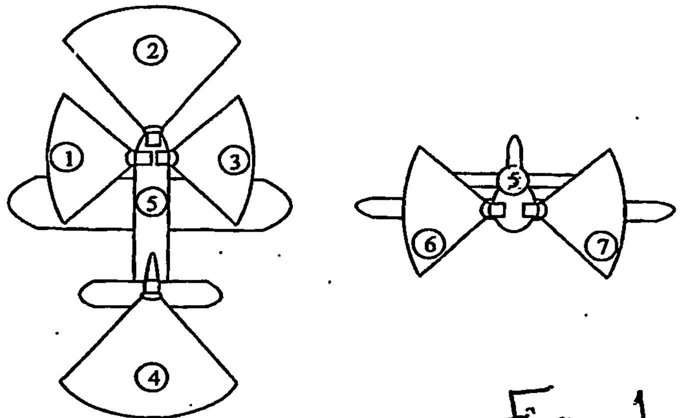


Fig. 1
Prior Art

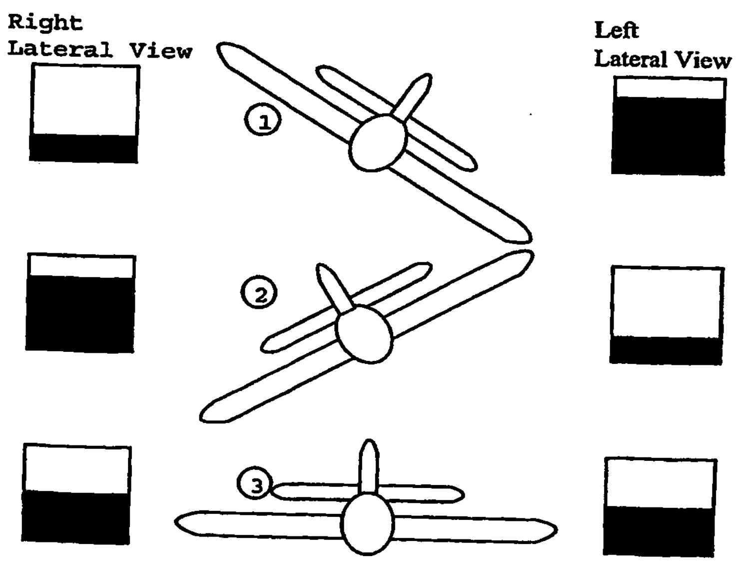
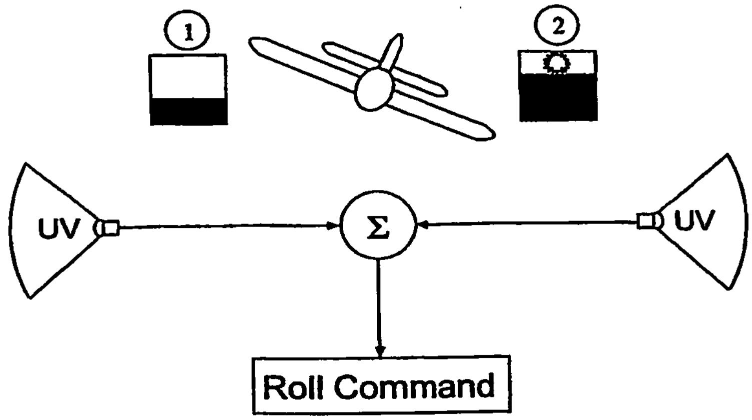


Fig. 2
Prior Art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2
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Σ
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Roll Command

Fig. 3

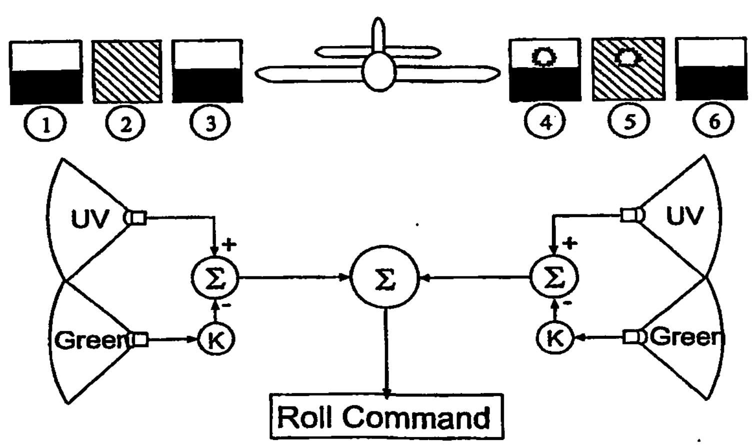
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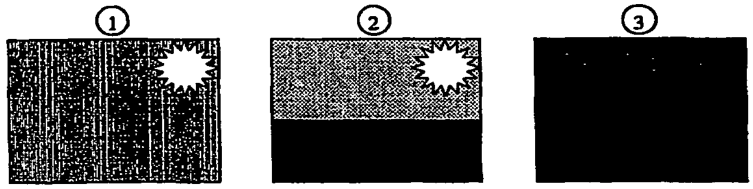
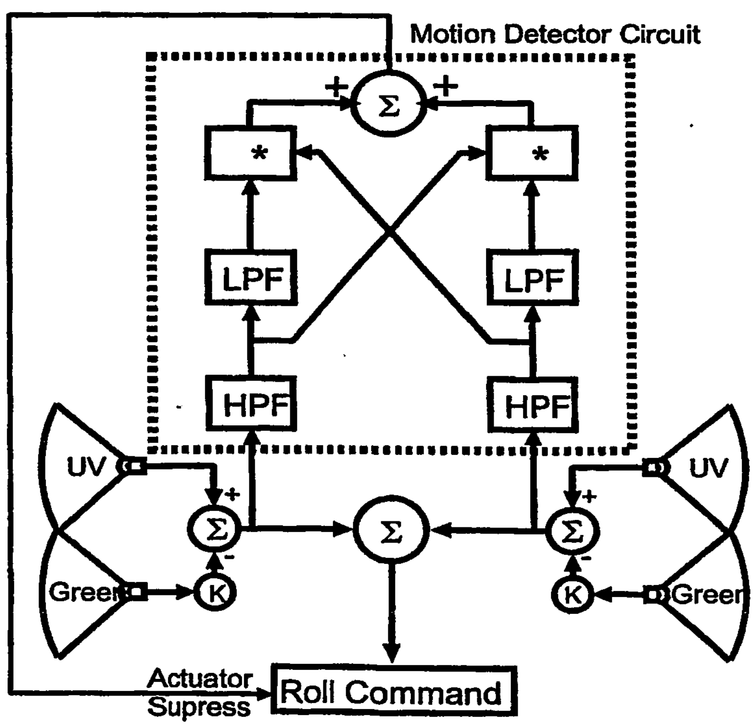
Fig. 4



1
2
3

Fig. 5



Motion Detector Circuit
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+
Σ
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LPF
LPF
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HPF
UV
UV
+
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Σ
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Green
Green
K
K
Actuator
Supress
Roll Command

Fig. 6

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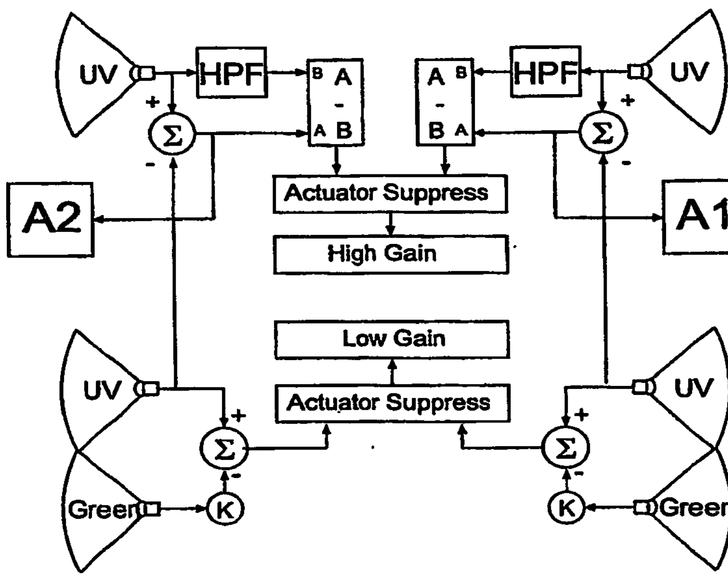

Figure 7: Addition of more radiation detectors provides greater flexibility. Angular motion can be computed with precision, allowing precise control surface deflections for angular disturbances. Precise bank and pitch angle control is possible using this sensor, as angular displacement from horizontal is directly measurable. Variables A1 and A2 provide the gradient of sky to ground intensity when divided by the angular separation between the to directions of view on each side of the craft. A long term average of the signals A1 and A2 would allow reasonable estimates of the signal to expect from ocelli to achieve a particular bank or climb angle.

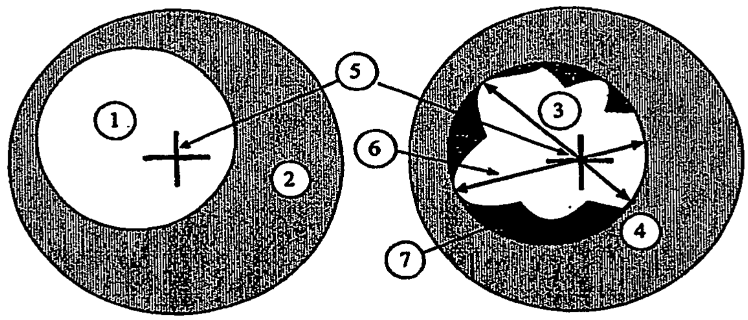

Figure 8: Considering a panoramic image it is possible to compute the most likely "up" direction by determining the optimal location of the horizon.

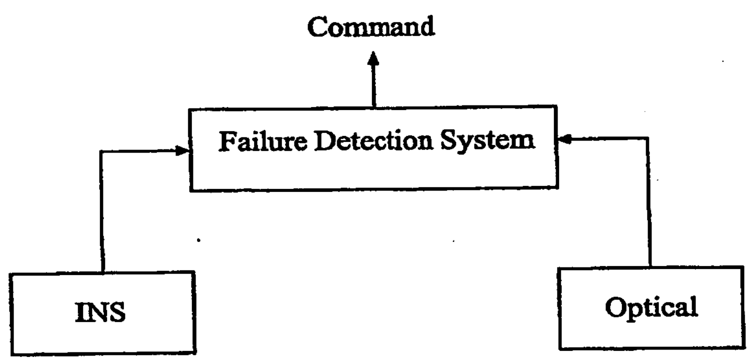

Figure 9: A horizon stabilization system is cheaper and lighter than an inertial measurement unit, yet can provide a valuable backup system in the event of the inertial unit failing. Many inertial units contain circuitry to detect failures in components, however it is not usually clear what action should be taken if the unit fails.

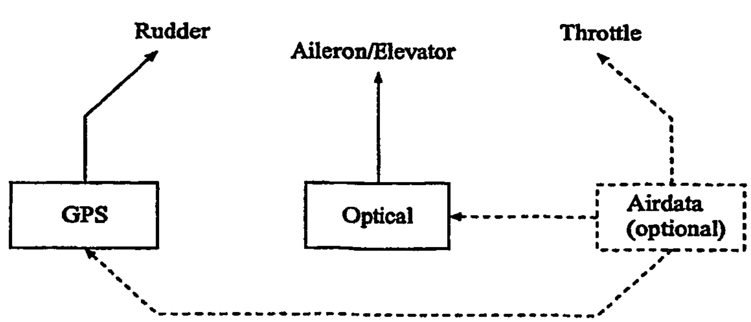

Figure 10: A horizon stabilization system is an inexpensive alternative to inertial measurement units for keeping an aircraft upright. With the addition of a GPS unit, a full navigating autopilot can be implemented.

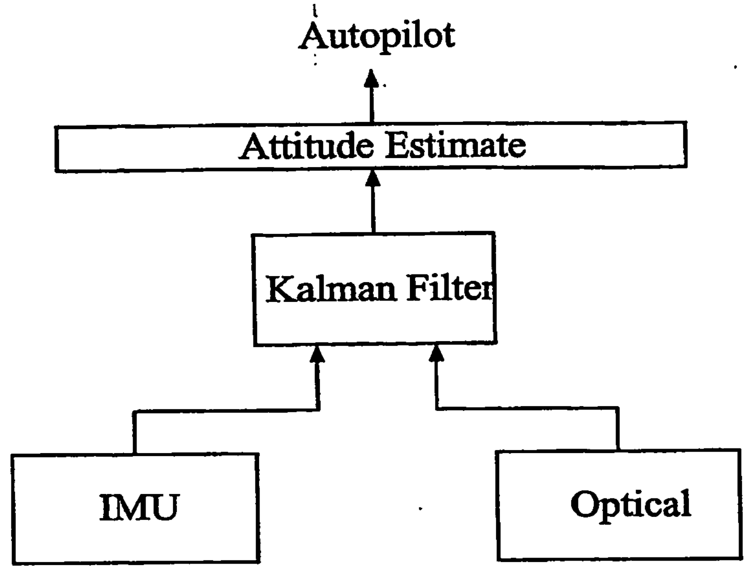

Figure 11: Combined inertial and horizon sensor units can complement each other to provide a better estimate of aircraft attitude.

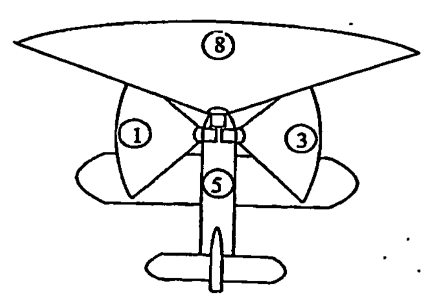

Fig. 12